

Model-dependent high-energy neutrino flux from Gamma-Ray Bursts

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The IceCube Collaboration recently reported a stringent upper limit on the high energy neutrino flux from GRBs, which provides a meaningful constraint on the standard internal shock model. Recent broad band electromagnetic observations of GRBs also challenge the internal shock paradigm for GRBs, and some competing models for γ -ray prompt emission have been proposed. We describe a general scheme for calculating the GRB neutrino flux, and compare the predicted neutrino flux levels for different models. We point out that the current neutrino flux upper limit already disfavors any dissipative photosphere model that invokes high energy proton acceleration at the same site, and challenges the internal shock model. If the neutrino flux upper limit continues to go down in the next few years, then it would suggest that the GRB emission site is at a larger radius than the internal shock radius or for some reason protons do not get accelerated to high energies at the site where γ -ray photons are produced. The larger-radius solution for the low neutrino flux from GRBs would provide support to magnetic dissipation models that invoke a large dissipation radius, such as the ICMART model.

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I. Introduction. — As energetic, non-thermal photon emitters, gamma-ray bursts (GRBs) have long been regarded as efficient cosmic ray accelerators [1]. If protons in a GRB jet can be accelerated to an energy E_p so that the condition

$$E_p E_\gamma \sim \frac{m_\Delta^2 - m_p^2}{2} \left(\frac{\Gamma}{1+z} \right)^2 = 0.147 \text{ GeV}^2 \left(\frac{\Gamma}{1+z} \right)^2 \quad (1)$$

is satisfied, significant neutrino emission is possible via the $p\gamma$ mechanism at the Δ -resonance. Here Γ is the bulk Lorentz factor, E_γ is photon energy in observer frame, $m_\Delta = 1.232 \text{ GeV}$ and $m_p = 0.938 \text{ GeV}$ are the rest masses of Δ^+ and proton, respectively. For GRBs, a guaranteed target photon source for $p\gamma$ interaction is the burst itself. For the typical peak photon energy $E_\gamma \sim$ several hundred keV, the corresponding neutrino energy

$$E_\nu \simeq 0.05 E_p \quad (2)$$

is in the sub-PeV regime [2] which is well suited for detection with the current generation of high energy neutrino detectors such as the IceCube [3]. Indeed over the years, the IceCube Collaboration have been searching for high energy neutrino signals coincident with GRBs in time and direction, and progressively deeper non-detection upper limits have been placed [4, 5], which are now beginning to constrain the standard GRB internal shock model [2]. The current IceCube upper limit was claimed to be at least a factor of 3.7 smaller than the theoretical predictions for neutrino flux from GRBs according to the internal-shock model, which has raised further doubt regarding the viability of GRBs as sources of UHECRs [5]. More detailed, follow-up, calculations [6–8] suggest that the current limit is still not deep enough to provide significant constraints on the validity of the internal shock model. However, the model would be severely challenged

if the upper limit continues to go down in the next few years.

On the other hand, besides the internal shock model, there have been other GRB prompt emission models proposed over the years, including dissipative photosphere models [9–11] and magnetic dissipation models at large radii [12, 13]. Recent GRB observations with Swift and Fermi missions have suggested that the simple fireball internal shock model cannot account for the rich data of GRB prompt emission [14], and these other mechanisms for GRB prompt emission become more attractive. The neutrino signal predictions of these prompt emission models could be very different from what is predicted for the internal shock model. The progressively stringent upper limit of neutrino flux would start to rule out some of these models. Since different models invoke different assumptions regarding the GRB jet composition, future neutrino data would hold the key to diagnose the poorly known GRB jet composition. In this paper, we develop a general method for calculating the neutrino flux for a wide variety of GRB prompt emission models, and discuss how the current upper limit constrains various models.

II. General formalism. Our general formalism closely follows the notations adopted by the IceCube Collaboration [4], but we make the following changes: (1) In all the previous GRB neutrino flux calculations, the internal shock model has been implicitly assumed, so that the radius where protons are accelerated and the radius where γ -ray photons are generated are both taken as

$$R = R_{\text{IS}} = \Gamma^2 c \delta t_{\text{min}} / (1+z), \quad (3)$$

where δt_{min} is the minimum variability time scale observed in a GRB light curve. This expression, even though widely used, is not relevant for models other than the internal-shock model. For instance, in the

dissipative photosphere models, the photosphere radius $R_{\text{ph}} < R_{\text{IS}}$, and δt_{min} could reflect the intrinsic variability time scale of the central engine, which could be larger than the angular spreading time defined by $R_{\text{ph}}/(\Gamma^2 c)$. The magnetic dissipation models (e.g. the Internal Collision-induced MAGnetic REconnection and Turbulence or ICMART model [12]) can have a GRB emission site $R > R_{\text{IS}}$. The rapid variability time scale δt in these models is related to the time scale of relativistic mini-jets in the emission region driven by relativistic turbulence or reconnection [12, 13, 15]. To account for these possibilities, in our formalism we consider the primary parameters to be R and Γ instead of δt and Γ . (2) In the internal shock model, γ -rays and neutrinos are generated by electrons and protons accelerated by the same shocks. And a parameter f_e (electron-to-proton energy ratio in the internal shocks) relates the neutrino flux to the observed γ -ray flux – the assumption being that electron energy is efficiently converted to γ -rays and neutrino flux is proportional to the energy in high energy protons. In the general formalism, we allow γ -ray photons and proton acceleration to occur at different locations. We therefore introduce a more general parameter $f_{\gamma/p}$ (Eq.9) to denote the ratio between photon luminosity and non-thermal proton luminosity, which reduces to f_e in any model that invokes the same site for photon production and proton acceleration (e.g. the internal shock model). (3) We generalize the previous low optical-depth treatment to also include very high optical-depth regime by invoking a more general $\epsilon_{\nu,1}$ (Eq.6). (4) We introduce another factor f_p (Eq.10) that represents the fraction of energy in those protons that can most efficiently produce neutrinos via the photo-pion process [6].

The general scheme for calculating neutrino flux is as follows: For an observed “Band”-function photon flux spectrum

$$F_\gamma(E_\gamma) = \frac{dN(E_\gamma)}{dE_\gamma} = f_\gamma \begin{cases} \left(\frac{\epsilon_\gamma}{\text{MeV}}\right)^{\alpha_\gamma} \left(\frac{E_\gamma}{\text{MeV}}\right)^{-\alpha_\gamma}, & E_\gamma < \epsilon_\gamma \\ \left(\frac{\epsilon_\gamma}{\text{MeV}}\right)^{\beta_\gamma} \left(\frac{E_\gamma}{\text{MeV}}\right)^{-\beta_\gamma}, & E_\gamma \geq \epsilon_\gamma \end{cases},$$

the observed neutrino number spectrum can be expressed as [2, 4]

$$F_\nu(E_\nu) = \frac{dN(E_\nu)}{dE_\nu} = f_\nu \begin{cases} \left(\frac{\epsilon_{\nu,1}}{\text{GeV}}\right)^{\alpha_\nu} \left(\frac{E_\nu}{\text{GeV}}\right)^{-\alpha_\nu}, & E_\nu < \epsilon_{\nu,1} \\ \left(\frac{\epsilon_{\nu,1}}{\text{GeV}}\right)^{\beta_\nu} \left(\frac{E_\nu}{\text{GeV}}\right)^{-\beta_\nu}, & \epsilon_{\nu,1} \leq E_\nu < \epsilon_{\nu,2} \\ \left(\frac{\epsilon_{\nu,1}}{\text{GeV}}\right)^{\beta_\nu} \left(\frac{\epsilon_{\nu,2}}{\text{GeV}}\right)^{\gamma_\nu - \beta_\nu} \left(\frac{E_\nu}{\text{GeV}}\right)^{-\gamma_\nu}, & E_\nu \geq \epsilon_{\nu,2} \end{cases},$$

where

$$\alpha_\nu = p + 1 - \beta_\gamma, \quad \beta_\nu = p + 1 - \alpha_\gamma, \quad \gamma_\nu = \beta_\nu + 2, \quad (4)$$

and p is the proton spectral index defined by $N(E_p)dE_p \propto E_p^{-p}dE_p$. The indices α_ν and β_ν are derived by assuming that the neutrino flux is proportional

to the $p\gamma$ optical depth $\tau_{p\gamma}$, which is roughly valid when $\tau_{p\gamma} < 3$. In this case, the first break

$$\epsilon_{\nu,1} = \epsilon_{\nu,1}^0 \equiv 7.3 \times 10^5 \text{ GeV} (1+z)^{-2} \Gamma_{2.5}^2 \epsilon_{\gamma,\text{MeV}}^{-1} \quad (5)$$

is defined by the break in the photon spectrum. For the case of high $p\gamma$ optical depth, the neutrino flux no longer significantly increases as $\tau_{p\gamma} > 3$ (essentially all the proton energy is given to pions). The neutrino spectrum may be still approximately delineated as the above broken power law form, with $\epsilon_{\nu,1}$ smaller by a factor $(f_\pi/3)^{\beta_\gamma-1}$. In general, one can write

$$\epsilon_{\nu,1} = \epsilon_{\nu,1}^0 \min(1, (f_\pi/3)^{1-\beta_\gamma}), \quad (6)$$

where

$$f_\pi \equiv \tau_{p\gamma}(E_p^p) \simeq \frac{\Delta R'}{\lambda'_{p\gamma}(E_p^p)} = 0.8 L_{\gamma,52} \Gamma_{2.5}^{-2} R_{14}^{-1} \epsilon_{\gamma,\text{MeV}}^{-1}, \quad (7)$$

is the $p\gamma$ optical depth for protons with energy E_p^p that interact with photons at the peak energy $E_\gamma^p \equiv \epsilon_\gamma$, $\lambda'_{p\gamma}(E_p^p)$ is the comoving proton mean free path for $p\gamma$ interaction at E_p^p , and $\Delta R'$ is the comoving width of causally connected region of the jet. The parameter f_π is also the ratio between comoving dynamical time and proton (with energy E_p^p) cooling time as a result of pion production [2]. The parameter R denotes the distance of proton acceleration site (rather than the photon emission site if the two sites are different) from the central engine. The second break energy in the neutrino spectrum,

$$\epsilon_{\nu,2} = 3.4 \times 10^8 \text{ GeV} (1+z)^{-1} \epsilon_B^{-1/2} L_{w,52}^{-1/2} \Gamma_{2.5}^2 R_{14} \quad (8)$$

is defined by the π^+ synchrotron cooling effect, above which the newly produced π^+ lose energy in a time scale shorter than the pion decay time scale. Here ϵ_B is the fraction of dissipated jet energy in magnetic fields, and L_w is the luminosity of the dissipated wind. We further define

$$f_{\gamma/p} \equiv \frac{L_\gamma}{L_p}, \quad (9)$$

and

$$f_p \equiv \frac{\int_{E_{p,1}}^{E_{p,2}} dE_p E_p^2 dN(E_p)/dE_p}{\int_{E_{p,min}}^{E_{p,max}} dE_p E_p^2 dN(E_p)/dE_p} \simeq \frac{\ln(\epsilon_{\nu,2}/\epsilon_{\nu,1})}{\ln(E_{p,max}/E_{p,min})} \quad (\text{for } p=2), \quad (10)$$

where $E_{p,1}$ & $E_{p,2}$ are proton energies corresponding to $\epsilon_{\nu,1}$ and $\epsilon_{\nu,2}$, respectively (Eq.2), and $E_{p,max}$ and $E_{p,min}$ are the maximum and minimum proton energy. One can then normalize the neutrino spectrum with the total photon fluence, i.e.

$$\int_0^\infty dE_\nu E_\nu F_\nu(E_\nu) = \frac{1}{8} \frac{f_p}{f_{\gamma/p}} [1 - (1 - \langle \chi_{p \rightarrow \pi} \rangle)^{f_\pi}] \times \int_{1 \text{ keV}}^{10 \text{ MeV}} dE_\gamma E_\gamma F_\gamma(E_\gamma), \quad (11)$$

where $\langle \chi_{p \rightarrow \pi} \rangle \simeq 0.2$ is the average fraction of energy transferred from protons to pions, and the factor $[1 - (1 - \langle \chi_{p \rightarrow \pi} \rangle)^{f_\pi}]$ is the fraction of proton energy that goes to pion production, which exceeds $\sim 50\%$ when $f_\pi > 3$ and quickly approaches 100% at larger f_π values. The coefficient $1/8$ is the product of $1/4$ (4 leptons share the energy of one π^+) and $1/2$ (on average roughly half of $p\gamma$ interactions go to the π^+ channel when all the π^+ processes besides Δ^+ resonance, e.g. direct-pion production, and multiple pion production, are taken into account).

III. Model-dependent neutrino flux. Below we apply the general formalism to different models.

(1) Internal shock (IS) model: Both photon emission and proton acceleration occur at $R_{\text{IS}} \sim 10^{13} - 10^{14}$ cm (Eq.3). One can make two simplifications. First, $f_{\gamma/p} = f_e$ can be adopted; second, $L_w = L_\gamma/\epsilon_e$ can be adopted, where ϵ_e is the fraction of jet energy in electrons, and fast cooling is assumed. The general formalism is then reduced to the IceCube formalism [4], except the additional f_p correction factor and the modification of $\epsilon_{\nu,1}$ (Eq.6).

(2) Dissipative photosphere (ph) model: According to this model, the prompt GRB spectrum is formed near the Thomson scattering photosphere $R_{ph} \simeq 3.7 \times 10^{11}$ cm $L_{w,52} \Gamma_{2.5}^{-3}$ [16]. In order to account for the observed non-thermal photon spectrum, it is required that significant energy dissipation and particle acceleration occur at moderate optical depths [9–11]. The heating processes include small-radius internal shocks (those with very short variability time scales $\delta t \ll \delta t_{min}$, so that the internal shock radius is smaller than R_{ph}), neutron-proton collisional heating, or magnetic dissipation in a magnetized wind with a striped wind geometry. For the neutron-proton collisional heating scenario [10], small-radius internal shocks are needed to induce collision. In these shocks, significant neutrino emission is possible if the synchrotron-cooling-limited maximum proton energy, $E_{p,max} = 1.3 \times 10^{19}$ eV $\Gamma_{2.5}^{3/2} R_{11}^{1/2} L_{w,52}^{-1/4} \epsilon_B^{-1/4} \zeta^{-1/2}$ (where ζ is a parameter of unity to delineate the uncertainty of comoving acceleration time scale with respect to the particle gyration radius over speed of light) exceeds the critical proton energy demanded by the Δ -resonance condition Eq.1. One can see that the condition is satisfied for typical parameters. For the magnetic-dissipation photosphere model [11], it has been argued that the reconnection process is able to accelerate protons to UHECRs [19]. So for all these dissipative photosphere models, it is likely that both photons and cosmic rays are generated at R_{ph} and significant neutrino emission is produced. Compared with the IS model, the main correction is that f_π increases by a factor of R_{IS}/R_{ph} , so that neutrino production is enhanced.

One way to lower the neutrino flux for the dissipative photosphere model is to assume that protons are not accelerated to high energies to satisfy the requirement of Eq.1 for pion production. Particle-in-cell simulations show that particle acceleration is inefficient in magnetized relativistic shocks [18]. However, internal shocks

are usually mildly-relativistic. Protons can be more efficiently accelerated than electrons, and it is possible to have proton accelerated in internal shocks even if the magnetization parameter (the Poynting-flux-to-matter-flux ratio) σ is as high as 0.1 [18]. Moreover, for a striped magnetic wind, internal shocks tend to facilitate reconnection [20], which would accelerate cosmic rays to high energies. It seems unlikely that proton acceleration is completely suppressed at a dissipative photosphere.

(3) Photosphere + internal shock (ph+IS) model: For any efficient dissipative photosphere model, $\sigma \leq 1$ is expected at the photosphere (otherwise the photosphere luminosity is suppressed by a factor $(1 + \sigma)$). Internal shocks would in any case develop at $R_{\text{IS}} > R_{ph}$, where $\sigma \ll 1$ and cosmic rays are accelerated. Even if photon emission at the internal shocks may be inefficient, photons emitted from the photosphere would in any case pass through the internal shock region and interact with the energetic protons there to produce neutrinos. Due to dissipation, on average, the Lorentz factor in the internal shocks is expected to be somewhat smaller than that in the photosphere. The comoving photon number density in the internal shock region would be somewhat higher at R_{IS} in the ph+IS model than in the IS model. This tends to increase the neutrino flux with respect to the IS model. The angular distribution of γ -ray photons in the proton shell comoving frame is expected to be confined to a narrow angle about the radial direction (because these photons originated at a much smaller radius), as opposed to isotropic distribution for the IS model. However, since protons are roughly isotropic in the comoving frame, the resulting efficiency of neutrino production would not be reduced [17]. Finally, the parameter $f_{\gamma/p}$ can be larger than f_e , since photons are likely generated more efficiently in photosphere than in internal shocks. Considering all these factors, we expect that the predicted neutrino flux level in the ph+IS model is roughly the same (within a factor of a few) as that in the IS model.

(4) The internal collision-induced magnetic reconnection and turbulence (ICMART) model and other large-radius magnetic dissipation models: The ICMART model [12] invokes a highly magnetized outflow, which remains un-dissipated up to a radius $R_{\text{ICMART}} > R_{\text{IS}}$. Emission from the photosphere and internal shocks is greatly suppressed. Internal shocks help to destroy the ordered magnetic fields, and a strong run-away magnetic dissipation process occurs at a larger radius $R_{\text{ICMART}} \sim 10^{15}$ cm. The f_π parameter is therefore smaller by a factor $R_{\text{ICMART}}/R_{\text{IS}} \sim (10 - 100)$. Since the photon emission and proton acceleration are in the same region, one can take $f_{\gamma/p} = f_e$ and $L_w = L_\gamma/\epsilon_e$. This model therefore predicts a much lower neutrino flux than the IS model. The same applies to other magnetic dissipation models that invoke a large emission radius e.g. [13].

We calculate the neutrino flux of a typical GRB in different models in Fig.1. We first calculate the neutrino flux within the IS model. We apply Eq.3, and adopt the

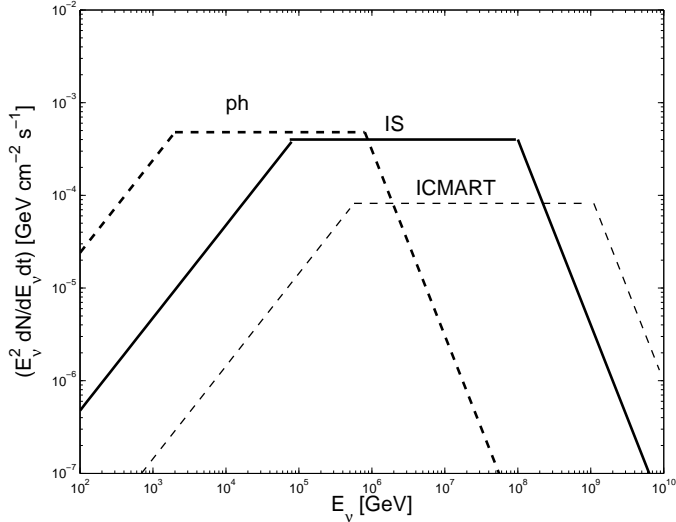


FIG. 1. The predicted neutrino flux for a typical GRB in three GRB prompt emission models: “ph”: dissipative photosphere model; “IS”: internal shock model; “ICMART”: internal-collision-induced magnetic reconnection and turbulence model. Model parameters: $L_{\gamma,52} = 1$, $\delta t = 0.1$ s, $\epsilon_{\gamma, \text{MeV}} = 0.2$, $\alpha_\gamma = 1$, $\beta_\gamma = 2$, $p = 2$, $z = 1$, $\Gamma = 250$, $f_e = 0.1$, $\epsilon_B/\epsilon_e = 1$, $R_{\text{ICMART}} = 10^{15}$ cm.

following values for the measurable parameters: $L_{\gamma,52} = 1$, $\delta t = 0.1$ s, $\epsilon_{\gamma, \text{MeV}} = 0.2$, $\alpha_\gamma = 1$, $\beta_\gamma = 2$, $p = 2$, and $z = 1$. For the IS model, one can write $f_{\gamma/p} = f_e$ and $L_{w,52} = L_{\gamma,52}/\epsilon_e$. We therefore have three free parameters Γ , f_e and ϵ_B/ϵ_e . It is reasonable to take $f_e \sim 0.1$ and $\epsilon_B/\epsilon_e \sim 1$. The largest uncertainty comes from Γ . The predicted neutrino flux is sensitive to Γ (e.g. $f_\pi \propto \Gamma^{-4}$ in the IS model). Γ can be constrained with several different methods [21–25], all with a lot of uncertainties. The IceCube Collaboration has used a “benchmark” value $\Gamma = 300$. The available data now show that Γ is not universal, and is correlated to L_γ [24, 25]. According to these measurements the average value of Γ is somewhat smaller than 300, which increases the expected neutrino

flux significantly (due to the strong Γ -dependence). We use the latest correlation [25]

$$\Gamma \simeq 250 L_{\gamma,52}^{0.30}, \quad (12)$$

to estimate Γ , which gives $\Gamma \sim 250$ for the example GRB.

Also shown in Fig.1 are the predicted neutrino fluxes for the dissipative photosphere model and the ICMART model (with $R_{\text{ICMART}} \sim 10^{15}$ cm). All other parameters remain the same. One can see that the ph model predicts a higher flux level with lower neutrino energies than the IS model, both favoring detections. The ICMART model predicts a much lower flux level than the IS model.

IV. Current status and future prospects. The continued search for neutrino signals from GRBs by the IceCube Collaboration is starting to pose meaningful constraints on GRB models. With the current limit, the IS model with the inclusion of a proper f_p correction and $\Gamma - L$ correlation just starts to barely violate the observational constraint [8]. The dissipative photosphere (ph) models are already disfavored, unless an unknown mechanism suppresses proton acceleration in the photosphere region. The ICMART model and other large-scale magnetic dissipation models are entirely consistent with the data. Thanks to the low neutrino background in the interested energy range, the upper limit would go down linearly with time. In a few more years, if high energy neutrinos are still not detected from GRBs, most matter-dominated GRB prompt emission models would be disfavored.

It is possible that different GRBs may have different degrees of magnetization, so that different models may apply in different bursts [26]. A more sophisticated analysis should invoke proper weights to different models to calculate the total neutrino flux. The upper limits would then give constraints on the weights of those models that invoke small emission radii.

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